Research Article

Experimental Study on Vacuum Grouting in Silty Sand Stratum

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Vacuum grouting is a new grouting method to control the groundwater in geotechnical engineering, which is often used in the strata where penetration grouting is difficult to reach an expected slurry diffusion radius, such as sand and silt strata. There are some theoretical studies about the influence of the vacuum field on the law of the slurry diffusion. However, the research on soil properties is rare. In this paper, through a self-designed grouting device, grouting in the silty sand after vacuum field action is studied. The test results indicate that with the increase in vacuum degree, the grouting capacity has an obvious improvement. When the vacuum degree is −15 kPa, the grouting capacity increased by 45.9% compared with the blank control group (0 kPa). Then, through the thermogravimetric analyzer and zeta potential meter the change of bound water and electric double layer in the silty sand after the effect of the vacuum field through a small device is studied. The results show that the effect of the vacuum field could make an influence on free water and loosely bound water, but the change of firmly bound water is unnoticeable. With the change of the vacuum degree, the variation of the water is increased. When the vacuum degree is −15 kPa, compared with the blank control group, the variable weight of free water is 5.79% and loosely bound water is 2.86%. As the bound water has a relationship with the effective void ratio, it can be inferred that the vacuum field may have an effect on the permeability coefficient of silty sand. These conclusions provide a reference for the theoretical study of vacuum grouting.

1. Introduction

Nowadays, grouting is a widely used method that can reinforce strata and control groundwater [1]. Traditional penetration grouting is to press the slurry with a certain pressure into the soil stratum, which needs to be pretreated. However, because the pressure is relatively low, it is difficult to inject into the fine-grained strata, such as sand and silt strata [2–5]. The principle of vacuum grouting is to generate a vacuum field through the vacuum well in the soil. Under the effect of this vacuum field, the air in the soil stratum was sucked away. At the same time, a negative pressure is created in the soil stratum. So, under the action of atmospheric pressure, the slurry is easier to inject into the soil [6,7]. Vacuum grouting is equivalent to increasing the pressure gradient of the slurry, so it can solve the problems that often appear in traditional methods, such as diffusion radius is not enough and ground surface heave [8–10]. Many scholars

have proved that this method is practicable. Wang [11] through the laboratory experiment, which used the vacuum grouting method, studied the diffusion law of slurry and found it has a noticeable water stop effect. Shen [12] used the vacuum grouting method to study the diffusion law in different strata and found that it can achieve directional grouting through controlling the vacuum field. Zhang [13] studied the distribution of the vacuum field in the fine sand stratum and found the diffusion law of slurry under different vacuum degrees.

In recent years, scholars have been studying a lot about the grouting combined with the vacuum in many engineering fields. Assaad and Daou [14] evaluated the effect of vacuuming on the amount of water extracted along with resulting changes in grout properties. Assaad et al. [15] assessed the effect of thixotropy on water retention and behavior of grouts placed using vacuum techniques. Peng et al. [16] proposed a new method that electroosmotic

grouting coupled with vacuum drainage at the cathode to improve the nonuniform effect of electroosmotic grouting. The experimental study shows that the treatment effect of electroosmotic grouting with vacuum drainage at the cathode is not only better than general electroosmosis methods but also more uniform than such methods. Huang et al. [17] revised the boundary conditions of Maag's spherical diffusion model according to the distribution law of negative vacuum pressure in the soil stratum and derived the vacuum-modified model. These studies have provided some useful methods and results to have further research on vacuum grouting. However, both theoretical research and laboratory tests only explore the effect of the vacuum field on slurry and there are few about grouting medium, such as soil and concrete. It is well known that there are some clay particles in silty sand. The surface of the clay particles is negatively charged, so there are lots of bound water in the soil; meanwhile, clay particles and bound water form an electric double layer [18]. Changes in bound water could cause changes in the effective void ratio, thereby affecting the permeability coefficient of the soil [19]. Therefore, the research about the influence of the vacuum field on soil properties is necessary.

The rest of this paper is organized as follows. Section 2 introduces the study method and material in detail. In Section 3, through a vacuum grouting test, the change law of grouting capacity in silty sand after the effect of the vacuum field is explored. Then, a small vacuuming device is used to study the change of soil properties under different vacuum degrees. Sections 4 and 5 analyze and discuss the results in the test. Finally, Section 6 draws several conclusions.

2. Methods and Materials

2.1. Methods. Vacuum grouting test was used to verify whether the grouting capacity increased after the silty sand was pumped by the vacuum field. If so, explore the relationship between grouting capacity and vacuum degree. Since the grouting capacity is related to the permeability coefficient of the silty sand and the permeability coefficient is related to the effective void ratio, the change in the effective void ratio can be characterized by the bound water. Microcosmic property test on silty sand was carried out to study the variation of bound water and Zeta potential with vacuum degree change. Figure 1 shows the route of the study.

2.2. Test Soil Sample. The silty sand used in the test is obtained from the floodplain of the Fenhe River in Taiyuan City, which is a major component of the floodplain strata. Table 1 shows the geotechnical properties of the silty sand, and Figure 2 plots the particle size distribution of silty sand according to a sieving test.

3. Test Device and Procedure

3.1. Vacuum Grouting Test

3.1.1. Test Device. Figure 3 shows the view of the test system. The vacuum grouting device consists of four parts: vacuum generation system, grouting system, vacuum monitoring system, and a test box.

(1) Vacuum Generation System. The vacuum generation system consists of an air compressor, a vacuum generator, a vacuum well, a vacuum gauge, and a pressure-regulating valve, which is connected by the rubber tube. Its working principle is similar to that of a jet pump. The compressed air generated by the air compressor is sucked at the lower end of the vacuum generator. As the air around the outlet of the throat is continuously sucked away, a negative pressure is generated in the vacuum well connected to the throat. The vacuum well draws the air in the soil of the test box. At this time, a vacuum field is formed around the vacuum well and then the soil has a certain vacuum degree.

The vacuum well used in the test is made of PVC pipe with a diameter of 40 mm and 100 mm in height. The middle of the well has some holes, and the diameter is 5 mm. Along the direction of the cylindrical busbar, the center distance of each hole is 15 mm. The distance in the circumferential direction of the adjacent two rows of holes is 15 mm and staggered with a height difference of 10 mm. A 100-mesh gauze was used to wrap around the hole in the vacuum well to prevent soil particles from entering the vacuum well during the test.

(2) Grouting System. The grouting system was used to inject the slurry into the soil and records the injected slurry capacity. It is composed of a funnel, a ball valve, a rotameter, and a PVC pipe. The pipe length is 350 mm, the bottom of the pipe is closed, and the bottom end of the pipe body was punched at about 100 mm. The hole has a diameter of 5 mm and was wrapped with a 100-mesh gauze.

(3) Monitoring System. The function of the vacuum monitoring system is to detect the vacuum degree in the test box. It consists of a vacuum gauge, ball valve, and PVC pipe. The pipe length is 350 mm, the bottom of the pipe is open, and the punching method is the same as the grouting system.

(4) Test Box. The test box was made of polymethyl methacrylate (PMMA) with a thickness of 7 mm, 600 mm in length, 200 mm in width, and 200 mm in height. In order to ensure the stability of the test box during the test, the length of the box was hooped with two stainless steel long rods.

3.1.2. Test Procedure. The test procedure was as follows:

(1) Installing the System. Place the vacuum well, vacuum gauge, and grouting pipe into the designated position of the test box. The sieved silty sand is added to the box until it is about 30 mm from the top. Connect the test system and check the status of each meter and switch.

(2) Sealing Test Box. The plastic film is laid on the upper part of the soil stratum, then poured into a preconfigured high-viscosity bentonite slurry with a thickness of 30 mm. A mud seal layer would form after 30 minutes.
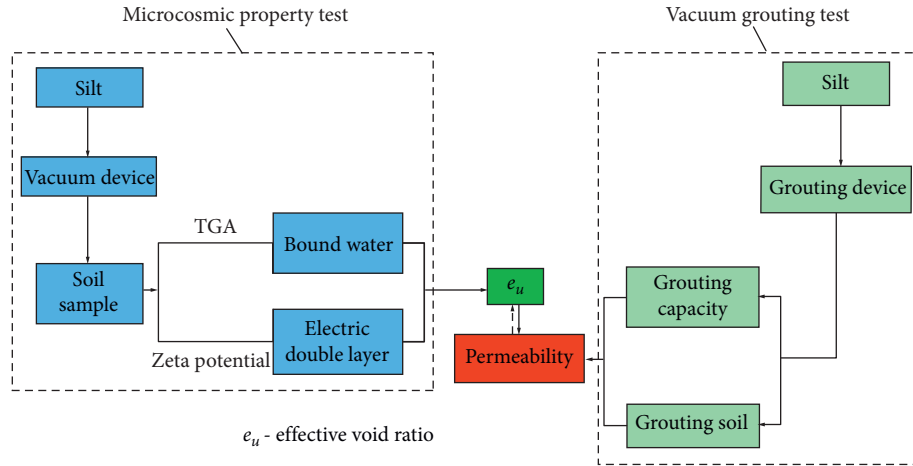
FIGURE 1: Route of the study.

(3) Dispensing the Slurry. The slurry used in the test was an acidic water glass chemical slurry, which has the advantages of good injectability and no pollution. According to the test requirements for the gel time and strength of the slurry, a water glass solution having a Baume degree of 30 and a dilute sulfuric acid solution having a mass fraction of 4.5% were preliminarily placed and separately placed.

(4) Grouting. Open the air compressor and adjust the pressure-regulating valve. Make the vacuum degree (Gauge 1) at −5 kPa for 15 min. Then stop the air compressor, mix the configured water glass solution, and pour the dilute sulfuric acid solution into the grouting funnel according to a specific ratio. Open the ball valve on the grouting pipe, then record the grouting amount for each time. After a while, when the slurry in the funnel no longer drops, the grouting is considered to be over. After an hour, dig out the grouting soil.

(5) Repeat step (1)–(3) at 0 kPa, −10 kPa, and −15 kPa.

3.2. Microcosmic Property Test

3.2.1. Test Device. Figure 4 shows the view of the property test system. The test system includes a microvacuum pump, a water-gas separation bottle, a test box, and a vacuum gauge. The microvacuum pump is manufactured by Kamoer corporation, and the model is KVP04-12. The test box is made of polymethyl methacrylate (PMMA), 130 mm in length, 100 mm in width, and 25 mm in height. The wall of the test box is 2.5 mm thick. The test box is divided into three warehouses. The left side is a vacuum chamber connected to a water-gas separation bottle and a microvacuum pump; the right side is the vacuum monitoring chamber; the middle part is a silty sand warehouse. The three parts are separated by two PMMA plates, each of which has eight small holes, 2 mm in diameter, and a 100-mesh gauze is attached to the holes to prevent the soil particles from being carried away during the pumping process.

TABLE 1: Parameters of the silty sand in laboratory test.

Parameters	Value
ρ_d	1.60 g/cm^3
P	1.89 g/cm^3
d_s	2.70
k	3.12 m/d
e	0.69
w	18.6%

ρ = density; ρ_d = dry density; d_s = specific gravity; e = void ratio; w = water content; k = hydraulic conductivity.

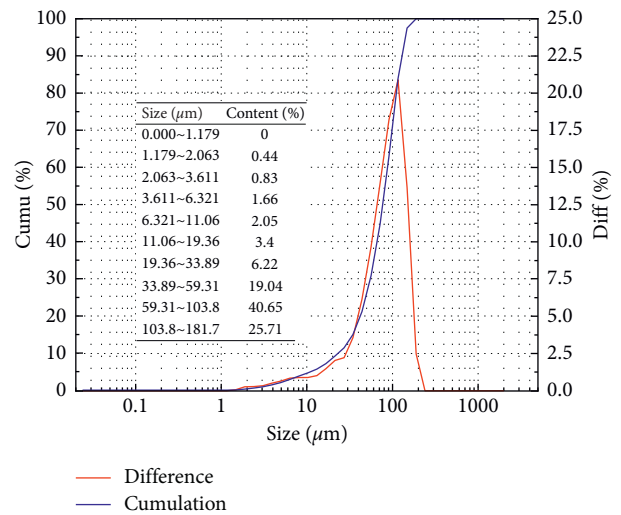
FIGURE 2: Grading curve of the silty sand used in the laboratory test.

3.2.2. Test Procedure. The test procedure was as follows:

(i) Connect the test equipment, then fill the test box with silty sand and seal the test box with glass glue.

(ii) Open the microvacuum pump, adjust the vacuum degree (Gauge 1) at −5 kPa for 15 min. After pumping, open the cover and sample the silty sand.
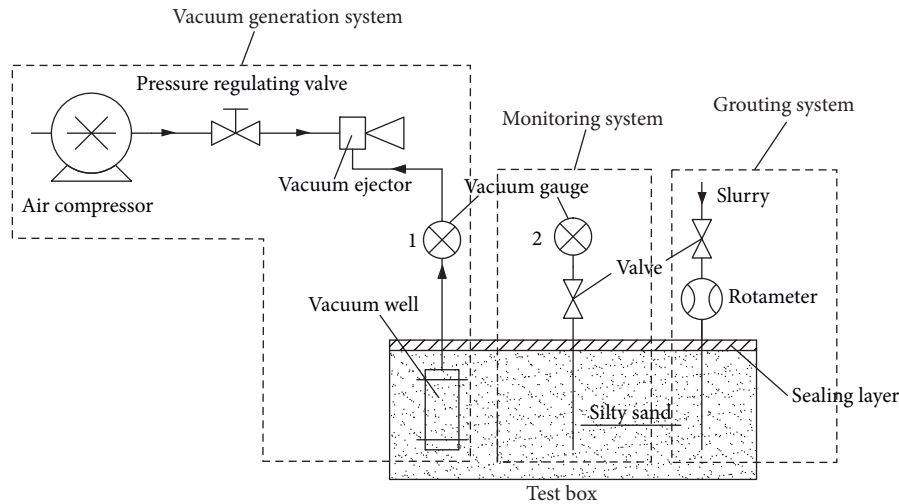
FIGURE 3: Schematic view of the grouting test system.

(iii) Conduct the thermogravimetric analysis and Zeta potential test on soil samples.

(iv) Repeat step $i \sim iii$ at 0 kPa, −10 kPa, and −15 kPa.

4. Results

4.1. Grouting Test. Figure 5 shows the variation of grouting capacity under different vacuum degrees. 0 kPa group is a blank control group, and grouting capacity increased with the time change, and also the other three groups have the same law. The injection rate of the slurry gradually becomes slower until it stops. With the change of vacuum degree, the grouting capacity increased, the change from 0 kPa to −5 kPa is most obvious, and the grouting capacity changes from 370 mL to 490 mL, increased by 32.4%. After −5 kPa, the rate of growth begins to slow down. Compared to the blank control group, when the vacuum degree increased to −15 kPa, the grouting capacity increased by 45.9%. After the action of the vacuum field, it has a positive effect on grouting capacity.

After the grouting finished for an hour, the soil was excavated and four grouting soils were obtained. As shown in Figure 6, both the diffusion radius of the slurry and the shape of grouting soil changed—the radius of the grouting soils changed from 28 mm to 40 mm. When the vacuum degree is relatively small, the grouting solid was shaped like a cylinder, and as the degree of vacuum gradually increases, the shape of the grouting soil gradually becomes an ellipsoid. The existence of the vacuum field makes the grouting capacity increase.

4.2. Property Test. By analyzing the thermogravimetric data of four groups of soil samples, it was found that 75°C and 120°C were two catastrophe points on the thermogravimetric curve. It can be inferred that before 75°C is the loss of free water, between 75°C and 120°C is the loss of loosely bound water, and after 120°C firmly bound water begins to separate. Wang and Chen [20] also got the same results according to the thermogravimetric experiment of soil. The
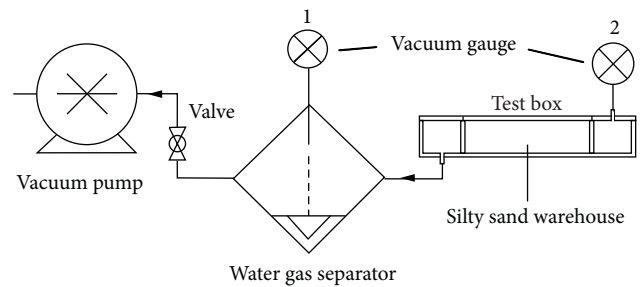

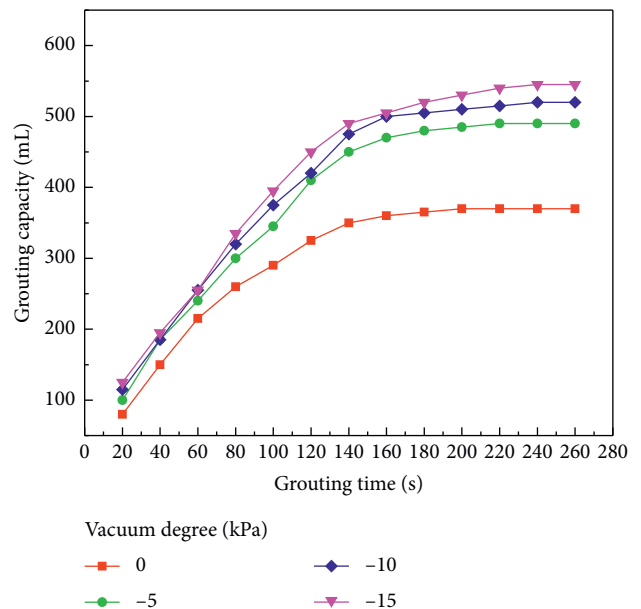FIGURE 4: Schematic view of the property test system.

FIGURE 5: Grouting capacity changes with time under different vacuum degrees.

weight of the soil samples decreases with the increase in the temperature. In order to analyze the variation of water loss in the soil sample, 0~75°C, 75~120°C, and 120~250°C were
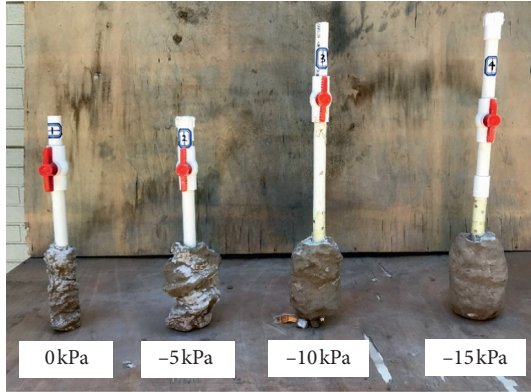
Figure 6: Grouting soils under different vacuum degrees.

selected as the three research intervals and 250°C is the end temperature of the test.

Figure 7 shows the weight change of silty sand under four vacuum degrees. The 0 kPa group is used as the blank control group. With the increase in vacuum degree, the total weight loss of water decreases from 18.4% to 9.41%. Among the three kinds of water, the content of the firmly bound water is the largest, free water is the second, and loosely bound water is the last. With the increase in the vacuum degree, free water has the largest weight loss, reaches to 5.79%; the loss of loosely bound water is 2.86%; however, there is almost no change in the firmly bound water.

Figure 8 plots the Zeta potential variation of soil samples under four vacuum degrees. As shown in Figure 8, as the vacuum degree increases, the Zeta potential changes from −18.8 mV to −15.4 mV. The existence of the vacuum field has a weak influence on the double electric layer, from 0 kPa to −5 kPa, and the variation of the Zeta potential is 1.4 mV, from −10 kPa to −15 kPa, and the variation is 0.9 mV. With the change of vacuum degree, the change rate of Zeta potential decreased.

5. Discussion

In the grouting test, there is a phenomenon that the amount of grouting does not increase with time, as shown in Figure 5. It is well known that the viscosity of a slurry is rheology and time-varying. According to Poiseuille's equation [21],

$$Q = \frac{\pi R^2}{8\eta} \cdot \frac{\Delta P}{r},$$ (1)

where Q is the grouting capacity per unit time; R is the soil pore radius; ΔP is the effective grouting pressure; r is the diffusion distance of the slurry; η is the viscosity of slurry.

According to equation (1), as the diffusion radius of the slurry increases, the flow resistance of the slurry increases. When the external pressure on the slurry balances the resistance of the slurry to flow, the slurry stops spreading and eventually forms a grouting soil.

According to the test results, due to the vacuum field, grouting capacity in the silty sand is improved. The pores in the soil can divide into effective pores and ineffective pores,
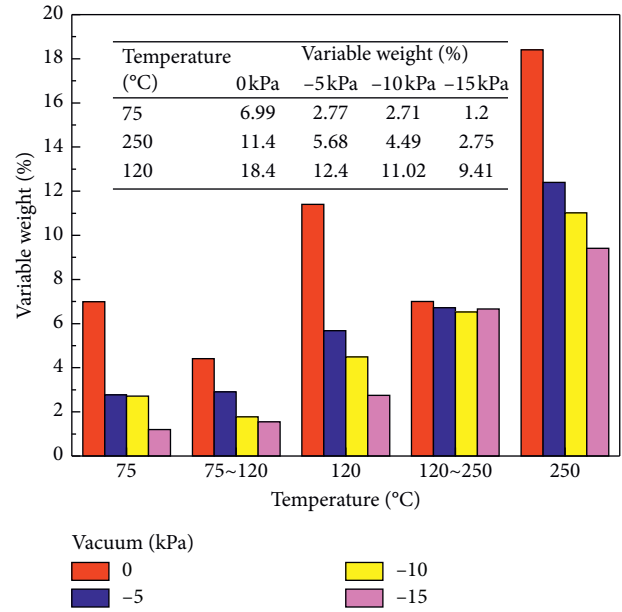

Temperature	Variable weight (%)			
(°C)	0 kPa	−5 kPa	−10 kPa	−15 kPa
75	6.99	2.77	2.71	1.2
250	11.4	5.68	4.49	2.75
120	18.4	12.4	11.02	9.41

Vacuum (kPa)
■ 0   □ −10
■ −5   □ −15

Figure 7: Weight change of different vacuum degrees.

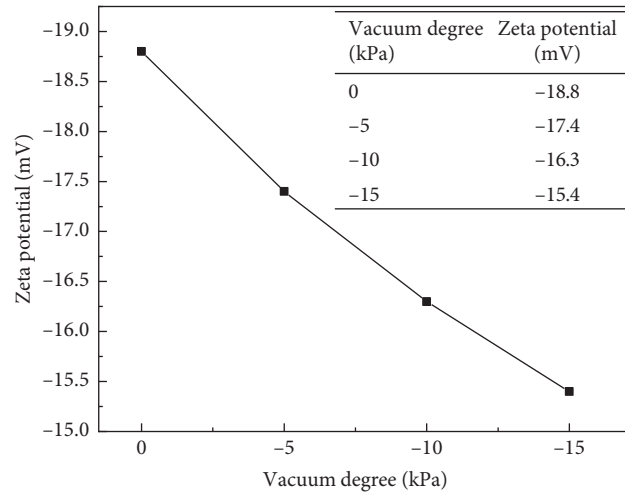| Vacuum degree (kPa)	Zeta potential (mV)
0	−18.8
−5	−17.4
−10	−16.3
−15	−15.4

Figure 8: Zeta potential change of different vacuum degrees.

while the bound water film occupies a part of the ineffective pores. Since the permeability coefficient of the soil is related to its effective void ratio when the effective void ratio increased, the permeability coefficient of silty sand increased and so the grouting capacity also increased.

The change in bound water under the vacuum field can be explained by the initial slope method. According to Darcy's law $v = ki$, where v is the penetration velocity and i is the hydraulic gradient, there is a layer of bound water film around the soil particles, so it is considered that there is an initial hydraulic slope in the clay soil [22]. The seepage needs to overcome the initial hydraulic gradient to occur [23]. As the hydraulic gradient increases, seepage occurs in the pores where the initial seepage cannot occur. The effect of the vacuum field is equivalent to adding a pressure head to the soil, and the hydraulic gradient is increased so that some loosely bound water that cannot be moved initially starts to flow.

The flow of the bound water makes the thickness of the bound water film changes. The thickness of the bound water film can be expressed by the potential value. Li [18] derived equation (2) for calculating the thickness of the loosely bound water film as

$$a \approx \frac{1}{E_0 v}\left(\frac{\lambda' k_0 T}{8\pi n_0}\right)^{1/2}, \quad (2)$$

where E_0 is the electrostatic unit of charge, the value is generally 4.8×10^{-10} esu; v is the charge ion valence, the value is ± 1; λ' is the dielectric constant of the loosely bound water film medium, $\lambda' = 80.0$; k_0 is the Boltzmann constant, $k_0 = 1.38 \times 10^{-23}$ J/K; T is the absolute temperature, taking $T = 293$ K (at 20°C); n_0 is the ion concentration at zero potential.

It can be seen from the formula that the maximum thickness a of the loosely bound water film is proportional to the product of the dielectric constant λ' and the absolute temperature T and is inversely proportional to the ion concentration n_0 in the solution. That is to say, the potential around the clay soil particles becomes small and the thickness of the loosely bound water film also decreases. The thickness of the bound water film could affect the effective porosity of the soil. Dang [24] deduced the expression of the effective void ratio as

$$e_u = e - a \cdot s, \quad (3)$$

where a is the weak combined water thickness and s is the specific surface area of the soil particles. According to equation (3), as the thickness of the combined water film decreases, the effective void ratio of the soil increases which lead to the improvement of the permeability coefficient.

At the same time, it can be known from the microcosmic property test that the effect of the vacuum field causes the free water and bound water to be lost. When the vacuum degree is −5 kPa, free water and loosely bound water has the maximum change rate, respectively, 4.22% and 1.5%; and when the vacuum degree is −10 kPa and −15 kPa, the change rate of free water and loosely bound water gradually decreases. According to the above analysis, the decrease of loosely bound water increases the effective void ratio of silty sand. At −5 kPa, the change rate of loosely bound water is the largest. Therefore, the grouting capacity change is most obvious in the grouting test.

6. Conclusions

In this paper, both vacuum grouting test and microcosmic property test are conducted to investigate the effect of the vacuum field to silty sand with different vacuum degrees. Further analysis is also carried out on the vacuum effect of loosely bound water and electric double layer in a silty sand stratum. The following conclusions can be drawn:

(1) Vacuum grouting test was performed to study the effect of the vacuum field to grouting capacity with different vacuum degrees. After the silty sand through the action of the vacuum field, as the vacuum degree increased from 0 kPa to −15 kPa, the grouting capacity increased from 370 ml to 540 ml and the growth of the grouting capacity reached 45.9%. As the degree of vacuum increases, the growth rate of grouting capacity tends to slow down.

(2) The result of the microcosmic property test shows the variation law of bound water and electric double layer in silty sand under different vacuum degrees. With an increase in the vacuum degree, the free water and loosely bound water are taken away by the vacuum field simultaneously. The variable weight of the loosely bound water is 2.86%; however, there is no change in the firmly bound water. So, as the loosely bound water and free water changes, it is indicated that the vacuum field may have an influence on the effective void ratio of the silty sand stratum.

Data Availability

The data used to support the findings of this study have not been made available because further research on this study has to be conducted.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

References

[1] J. Yoon and C. El Mohtar, "Groutability of granular soils using sodium pyrophosphate modified bentonite suspensions," *Tunnelling and Underground Space Technology*, vol. 37, pp. 135–145, 2013.

[2] C. A. Anagnostopoulos, "Laboratory study of an injected granular soil with polymer grouts," *Tunnelling and Underground Space Technology*, vol. 20, no. 6, pp. 525–533, 2005.

[3] S. B. Im, S. Hurlebaus, and D. Trejo, "Effective repair grouting methods and materials for filling voids in external post-tensioned tendons," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2172, no. 1, pp. 3–10, 2010.

[4] J. Lv, Y. Chi, C. Zhao, Y. Zhang, and H. Mu, "Experimental study of the supercritical CO_2 diffusion coefficient in porous media under reservoir conditions," *Royal Society Open Science*, vol. 6, no. 6, Article ID 181902, 2019.

[5] J. Dai, C. Liu, M. Li, and Z. Song, "Influence of principal stress effect on deformation and permeability of coal containing beddings under true triaxial stress conditions," *Royal Society Open Science*, vol. 6, no. 2, Article ID 181438, 2019.

[6] J. Zhang, Y. Liu, N. Zhou, and M. Li, "Pore pressure evolution and mass loss of broken gangue during the seepage," *Royal Society Open Science*, vol. 5, no. 10, Article ID 180307, 2018.

[7] S. ÇubMe, P. Majedi, and S. Akbulut, "Granular soil improvement by using polyester grouts," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 43, no. 3, pp. 599–606, 2019.

[8] M. Kalenik, "Empirical formulas for calculation of negative pressure difference in vacuum pipelines," *Water*, vol. 7, no. 10, pp. 5284–5304, 2015.

[9] W.-C. Cheng, Q.-L. Cui, J. Shen, A. Arulrajah, and D.-J. Yuan, "Fractal prediction of grouting volume for treating karst caverns along a shield tunneling alignment," *Applied Sciences*, vol. 7, no. 7, p. 652, 2017.

[10] H. Strømsvik, "The significance of hydraulic jacking for grout consumption during high pressure pre-grouting in Norwegian tunnelling," *Tunnelling and Underground Space Technology*, vol. 90, pp. 357–368, 2019.

[11] Y. Wang, "Research on gelatinizing properties of the acidic soluble glass and the design of vacuum grouting technology," MS thesis, China University of Geosciences, Beijing, China, 2013.

[12] G. Shen, "Research on simulation test of vacuum grouting under different stratum," MS thesis, China University of Geosciences, Beijing, China, 2014.

[13] L. Zhang, "Research on simulation test of vacuum grouting under silty sand stratum," MS thesis, China University of Geosciences, Beijing, China, 2015.

[14] J. J. Assaad and Y. Daou, "Cementitious grouts with adapted rheological properties for injection by vacuum techniques," *Cement and Concrete Research*, vol. 59, pp. 43–54, 2014.

[15] J. J. Assaad, Y. Daou, and J. Harb, "Influence of thixotropy on performance of grouts placed using vacuum injection techniques," *ACI Materials Journal*, vol. 112, no. 2, pp. 189–198, 2015.

[16] J. Peng, H. Ye, and A. N. Alshawabkeh, "Soil improvement by electroosmotic grouting of saline solutions with vacuum drainage at the cathode," *Applied Clay Science*, vol. 114, pp. 53–60, 2015.

[17] F. Huang, J. Lyu, H. Gao, and G. Wang, "Modified Maag's spherical diffusion model of vacuum grouting," *Mathematical Problems in Engineering*, vol. 2018, Article ID 1758651, 7 pages, 2018.

[18] G. Li, *Advanced Soil Mechanics*, Tsinghua University Press, Beijing, China, 2004.

[19] B. Dolinar and B. Trček, "A new relationship between the mobile and the adsorbed water in fine-grained soils using an effective void-ratio estimation," *Bulletin of Engineering Geology and the Environment*, vol. 78, no. 6, pp. 4623–4631, 2019.

[20] P. Wang and D. Chen, "The determination of water content and bound water type on hydro-clay surface by thermal-weightlessness," *Journal of Southwest Petroleum Institute*, vol. 28, no. 1, pp. 52–55, 2006.

[21] J. Wang, *Theories and Engineering Examples of Rock and Soil Grouting*, Science Press, Beijing, China, 2001.

[22] T. Qi, K. Xie, A. Hu, and Z. Zhang, "Laboratorial study of non-Darcy seepage in Xiaoshan clay," *Journal of Zhejiang University: Engineering Science*, vol. 41, pp. 1023–1028, 2007, in Chinese.

[23] D. Swartzendruber, "Modification of Darcy's law for the flow of water in soils," *Soil Science*, vol. 93, no. 1, pp. 22–29, 1962.

[24] F. Dang, H. Liu, X. Wang, H. Xue, and Z. Ma, "Empirical formulas of permeability of clay based on effective pore ratio," *Chinese Journal of Rock Mechanics and Engineering*, vol. 34, pp. 1909–1917, 2015, in Chinese.